The Kr2Det project: Search for mass-3 state contribution $|U_{e3}|^2$ to the electron neutrino using a one reactor - two detector oscillation experiment at Krasnoyarsk underground site.

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Abstract

The main physical goal of the project is to search with reactor antineutrinos for small mixing angle oscillations in the atmospheric mass parameter region around $\Delta m^2_{atm} \sim 2.5 \times 10^{-3}$ eV^2 in order to find the element U_{e3} of the neutrino mixing matrix or to set a new more stringent constraint (U_{e3} is the contribution of mass-3 state to the electron neutrino flavor state). To achieve this we propose a "one reactor - two detector" experiment: two identical antineutrino spectrometers with ~50 ton liquid scintillator targets located at ~100 m and ~1000 m from the Krasnoyarsk underground reactor (~600 mwe). In no-oscillation case ratio of measured positron spectra of the $\bar{\nu}_e + p \to e^+ + n$ reaction is energy independent. Deviation from a constant value of this ratio is the oscillation signature. In this scheme results do not depend on the exact knowledge of the reactor power, $\bar{\nu}_e$ spectra, burn up effects, target volumes and, which is important, the backgrounds can periodically be measured during reactor OFF periods. In this letter we present the Krasnoyarsk reactor site, give a schematic description of the detectors, calculate the neutrino detection rates and estimate the backgrounds. We also outline the detector monitoring and calibration procedures, which are of a key importance. We hope that systematic uncertainties will not accede 0.5% and the sensitivity $U^2_{e3} \approx 4 \times 10^{-3}$ (at $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2) can be achieved.

1 Introduction

The Super-Kamiokande studies of atmospheric neutrinos [1] found intensive ($\sin^2 2\theta_{atm} > 0.9$) $\nu_\mu \to \nu_x$ oscillations and have confined the mass parameter to the interval $1.4\times10^{-3} < \Delta m^2_{atm} < 4.2\times10^{-3}$ eV^2 with $\Delta m^2_{atm} = 2.5\times10^{-3}$ eV^2 as the most probable value. The $\nu_\mu \to \nu_\tau$ has been found to be the dominant channel of the atmospheric neutrino oscillations, while much place is left also for the $\nu_\mu \to \nu_{\mu,\tau}$ transitions.

The ~ 1 km baseline reactor experiment CHOOZ [2] searched for electron antineutrino disappearance in the atmospheric mass parameters region. No oscillation have been found (Fig.1, curve "CHOOZ"):

$$\sin^2 2\theta_{CHOOZ} \le 0.14 \quad (90\%\ \mathrm{CL\ at}\ \Delta m^2 = 2.5\times10^{-3}\mathrm{eV}^2),$$
$$\sin^2 2\theta_{CHOOZ} \le 0.19 \quad (\mathrm{at}\ \Delta m^2 = 2.0\times10^{-3}\mathrm{eV}^2) \qquad (1)$$

The reactor neutrino mixing parameter $\sin^2 2\theta$ in atmospheric mass parameters region plays an important role in the neutrino oscillation physics. In three active neutrino mixing scheme with normal neutrino mass hierarchy it is expressed trough the contribution of the mass-3 eigenstate to the electron neutrino flavor state $U_{e3} = \sin\theta_{13}$,:

$$\sin^2 2\theta_{CHOOZ} = \sin^2 2\theta_{13} = 4|U_{e3}|^2(1 - |U_{e3}|^2) \qquad (2)$$

We mention also that with nonzero value of U_{e3} in the lepton sector the CP violation effects can exist.

The negative results of the CHOOZ experiment impose important constraint:

$$\sin^2 2\theta_{13} \le 0.14,\ |U_{e3}|^2 \le 3.6\times10^{-2}\ (\ \mathrm{at}\ \Delta m^2 = 2.5\times10^{-3}\mathrm{eV}^2) \qquad (3)$$

The quantity $\sin^2 2\theta_{13}$ can be hundreds and thousands times smaller than present CHOOZ limits. In this case necessary sensitivity can, in distant future and in several steps, be achieved at Neutrino Factories in experiments using hundred and thousand kt detectors located at a few thousand km from the accelerator neutrino source (For review see Ref. [3]).

The first step can, however, be done sooner (and cheaper) at reactors as has been discussed since 1999 y. [4,5]. Recently an idea to search for U_{e3} at reactors in Japan was published [6]. To do this first step is still more important because no physical reason is known why $\sin^2 2\theta_{13}$ should be very small. It may quite happen that this quantity is only several times smaller than present upper limits (1).

The main physical goals of the reactor experiment considered here are:

- To obtain new information on the electron neutrino mass composition (U_{e3}),
- To provide normalization for future experiments at accelerators,
- To achieve better understanding of the role ν_e can have in the atmospheric neutrino phenomena.

The main practical goal is to decrease, relative to CHOOZ, statistic and systematic uncertainties as much as possible.

Analysis of all available solar neutrino data (Ref [7]) confirms the LMA MSW as the most probable solution with the best fit value of the solar neutrino mass parameter $\Delta m^2_{sol} \approx 6 \times 10^{-5}$ eV^2. We assume therefore that

$$\Delta m^2_{sol} \ll \Delta m^2_{atm} = m_3^2 - m_2^2 \approx m_3^2 - m_1^2 \tag{4}$$

and use in this paper two mode expression for the reactor antineutrino survival probability $P(\bar{\nu}_e \to \bar{\nu}_e)$:

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta \cdot \sin^2 \left(\frac{1.27 \Delta m^2 L}{E} \right) \tag{5}$$

where L(m) is the reactor - detector distance and E (MeV) is the antineutrino energy. There is however some probability that Δm^2_{sol} is not so small as assumed above. In this case $\Delta m^2_{sol}/\Delta m^2_{atm}$ cannot be neglected and somewhat more complicated expressions for $P(\bar{\nu}_e \to \bar{\nu}_e)$ should be used as discussed in Refs [6, 8].

Reactor antineutrinos have a continues energy spectrum and are detected via the inverse beta-decay reaction

$$\bar{\nu}_e + p \to e^+ + n \tag{6}$$

The visible positron energy E_e is related to the $\bar{\nu}_e$ energy as

$$E_e = E - 1.80 + E_{annih} \approx E - 0.8 \tag{7}$$

Typical positron energy spectrum is shown in Fig. 2

2 One reactor - two detector scheme

Two identical liquid scintillation spectrometers are stationed at distances $L_{far} \approx 1000$ m (far position) and $L_{near} \approx 115$ m from the underground Krasnoyarsk reactor. (Fig. 3) The overburden at Krasnoyarsk is ~ 600 m.w.e., which is twice as much as in the CHOOZ experiment. (At short distances form the reactor the one reactor - 2 detector approach was first probed at Rovno [9] and later successfully used at Bugey [10])

Two types of analysis can be used. Analysis I is based on comparison of the shapes of positron spectra $S(E_e)_{far}$ and $S(E_e)_{near}$ measured simultaneously in two detectors. In no oscillation case the ratio $S(E_e)_{far}/S(E_e)_{near}$ is energy independent. Small deviations from the constant value of this ratio

$$X_{shape} = C \cdot \frac{1 - \sin^2 2\theta \cdot \sin^2\left(\frac{1.27\Delta m^2 L_{far}}{E}\right)}{1 - \sin^2 2\theta \cdot \sin^2\left(\frac{1.27\Delta m^2 L_{near}}{E}\right)} \tag{8}$$

are searched for oscillation parameters.

In the one reactor - two detector scheme

- Results of the Analysis I do not depend on the exact knowledge of the reactor power, absolute $\bar{\nu}_e$ flux and energy spectrum, burn up effects, absolute values of hydrogen atom concentrations, detection efficiencies, target volumes and reactor - detector distances.

- At Krasnoyrsk the detector backgrounds can be measured during reactor OFF periods, which periodically follow 50 daylong reactor ON periods.

Calculated ratios $S(E_e)_{far}/S(E_e)_{near}$ for a set of oscillation parameters are shown in Fig. 4.

Analysis II is based on the ratio of the total number of neutrinos N_{far}, N_{far} detected at two distances:

$$X_{rate}(\sin^2 2\theta, \Delta m^2) = \left(\frac{L_{far}}{L_{near}}\right)^2 \cdot \left(\frac{V_{near}}{V_{far}}\right) \cdot \left(\frac{\epsilon_{near}}{\epsilon_{far}}\right) \cdot \left(\frac{N_{far}}{N_{near}}\right) \tag{8$'$}$$

$V_{far}, V_{near}, \epsilon_{far}, \epsilon_{near}$ are the target volumes and neutrino detection efficiencies. In no oscillation case $X_{rate} = 1$.

Analysis II is also independent of the exact knowledge of the reactor neutrino flux and energy spectrum. The absolute values of detection efficiencies are practically canceled, only their small difference is to be considered here while the ratios $(L_{far}/L_{near})^2$ and (V_{near}/V_{far}) should be known accurately.

3 Detectors

A miniature version of the KamLAND [11] and BOREXINO [12] and a scaled up version of the CHOOZ three - concentric zone detector design is chosen for the constraction of the spectrometers (Fig. 5). At this stage we consider 4.7 m diameter liquid scintillator target, enclosed in transparent spherical balloon. The target is viewed by ∼800 8-inch EMI-9350 (9350 - 9356) photomultipliers trough ∼90 cm layer of mineral oil of the zone-2 of the detector. The PMT's of this type have successfully been used in the CHOOZ experiment and are used now in the BOREXINO and SNO detectors [13]. A 20% light collection and 150 - 200 photoelectron signal is expected for 1 MeV positron energy deposition. The PMT's are mounted on the stainless steel screen, which separates external zone-3 from the central zones of the detector. The ∼75 cm thick zone-3 is filled with mineral oil (or liquid scintillator) and serves as active (muon) and passive shielding from the external radioactivity.

4 Detector calibrations and monitoring; systematic uncertainties

The ratio of measured positron spectra $S(E_e)_{far}/S(E_e)_{near}$ (Eq. 8) can be slightly distorted because of relative difference in response functions of the two "identical" spectrometers.

The goal of calibration procedures we consider is to measure this difference and introduce necessary corrections. This can be done by a combination of different methods. First we consider periodic control of the energy scales in many points using γ-sources shown by arrows in Fig. 2. A useful continuous monitoring of the scales at 2.23 MeV can provide neutrons produced by trough going muons and captured by the target protons during veto time.

The second method uses small spontaneous fission ^{252}Cf or ^{238}U sources periodically placed in the detectors. These sources generates continuous energy spectrum due to prompt fission gammas and neutron recoils (the dashed line in Fig.2.). Deviation from unity of the measured spectra can be used to calculate relevant corrections.

We hope that systematic uncertainty due to detector spectrometric difference essential for Analysis I can be controlled down to 0.5%.

In Analysis II the systematic uncertainty in the quantity $(L_{far}/L_{near})^2 \cdot (V_{near}/V_{far}) \cdot (\epsilon_{near}/\epsilon_{far})$ in Eqs (8') can hopefully be kept within 0.8%.

5 Scintillator

The final choice of the scintillator has not been made so far. We hope for progress in manufacturing Gd ($\sim$0.9 g/liter) loaded scintillators to improve the response to neutrons and suppress accidentals, which originate from U/Th gammas coming from surrounding rock. The Palo Verde Gd-scintillator showed better stability than the scintillator used in CHOOZ. The LENS project considers scintillators with rare earth contents as high as $\sim$50 g/liter.

Currently we consider no-Gd scintillator based on the mixture of isoparaffin or mineral oil and pseudicumene ($\sim$20%) with $\sim$2g/liter PPO as primary fluor. This scintillator has C/H ratio 1.85, density 0.85 kg/liter and 0.785×10^{29} H atoms per ton.

6 Neutrino detection rates and backgrounds

The neutrino events satisfy the following requirements: (i) a time window on the delay between e^+ and neutron signals $2-600$ μs, (ii) energy window for the neutron candidate $1.7-3.1$ MeV and for e^+ $1.2-8.0$ MeV, (iii) distance between e^+ and neutron less than 100 cm. At this stage no pulse shape analysis to reject proton recoils is planned.

Under these assumptions neutrino detection efficiency of 75% was found and neutrino detection rate $N(e^+, n) = 55$/day calculated for the far detector.

The time correlated background 0.1 per day per one target ton was found by extrapolation of the value 0.25/per day per target ton measured at CHOOZ:

$$\text{CHOOZ (300 mwe)},\ 0.25/\text{day}\cdot\text{ton} \rightarrow \text{Kr2Det (600 mwe)},\ 0.1/\text{day}\cdot\text{ton} \tag{9}$$

The accidental coincidences come from the internal radioactivity of detector materials and U and Th contained in the surrounding rock. The internal component of the background was estimated to be less 0.3/day, which is an order of magnitude smaller than the rate of the correlated background (see hep-ph/0109277). In contrast to the KamLAND and Borexino experiments three orders higher concentrations of U, Th, K and Rn can be tolerated in the liquids used in the Kr2Det case.

First estimations of accidentals coming from the radioactivity of the rock showed however that external passive shielding of the detector should be increased in case scintillator without Gd is used as the neutrino target.

Calculated neutrino detection rates $N(e^+, n)$ and backgrounds for scintillator with no Gd are summarized in the Table.

Table 1:

Parameter	Distance, m	Target, mass, ton	$N(e^+, n)$, day^{-1}	$N(e^+, n)$, year^{-1*}	Backgr., day^{-1} correl.	accid.**
Far detector	1000	46	55	$16.5 \cdot 10^3$	5	~0.3
Near detector	115	46	4200	$12.5 \cdot 10^5$	5	~0.3

* 300 days/year at full power.

** due to internal radioactivity of the detector materials only.

7 Expected results and Conclusions

Expected 90% CL constraints on the oscillation parameters (Fig. 1, curves K2Det) are obtained for 40000 detected $\bar{\nu}_e$ in the far detector (750 days of full power). The systematic uncertainties σ_{shape}= 0.5% in the Analysis I ("shape") and σ_{rate}= 0.8% in the Analysis II ("rate") have been assumed. The "shape" analysis is somewhat more sensitive and can shift (at $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2 the $\sin^2 2\theta$ upper limit from 0.14 (CHOOZ) to 0.017.

The one reactor - two detector approach fully eliminates uncertainties associated with the reactor neutrino source inherent to the absolute method used at CHOOZ.

Small relative difference in conceptually identical detector properties can be minimized through calibration and monitoring procedures.

The detector backgrounds can be measured during reactor OFF periods, which periodically follow 50 daylong reactor ON periods.

Good signal to background ratio can be achieved due to sufficiently deep underground position of the detectors.

High statistics can be accumulated in reasonably short time period using detectors with ~45 ton targets, which are relatively small if compared to modern neutrino detectors.

Neutrino community has accumulated positive experience in building and running 3 concentric zone detectors similar to the Kr2Det detectors.

We conclude that proposed study is feasible and that new important information on the electron neutrino internal structure ($\sin^2 2\theta_{13}$) can be obtained.

Acknowledgments

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References

[1] S. Fukida et al. (Superkamiokande Collaboration), Phys. Rev. Lett. 85 3999 (2000), hep-ex/0009001)

[2] M. Apollonio et al., CHOOZ Collaboration, Phys. Lett. B 466 415 (1999).

[3] S. Geer, Comments on Modern Physics v.2 No6, 284 (2002), (hep-ph/0210113).

[4] L. Mikaelyan, V. Sinev, Phys. Atom. Nucl. 63 1002 (2000), (hep-ex/9908047);

[5] L. Mikaelyan, Nucl. Phys.B (Proc. Suppl.) 87 284 (2000), hep-ex/9910042; L. Mikaelyan, Nucl. Phys. B (Proc. Suppl.) 91 120 (2001), (hep- ex/0008046). Yu. Kozlov, L. Mikaelyan, V. Sinev, (hep-ph/0109277).

[6] H. Minakata et al. hep-ph/0211111.

[7] A. Yu. Smirnov, hep-ph/0209131.

[8] S. Schoenert, T. Lasserre, L. Oberauer, hep-ex/0203013.

[9] S. Ketov et al., Zhetp Letters v 55, 544 (1992).

[10] Y. Declais et al., Nucl. Phys. B 434 503 (1995)

[11] A. Piepke, for the KamLAND Collaboration, Nucl. Phys. B 91 99 (2001).

[12] G. Alimonti et al., BOREXINO collaboration, Astropart. Phys. 16 205 (2002).

[13] A. Baldini, C. Bemporad et al., NIM A 372 207 (1996).

A Neutrino site at Krasnoyarsk

The reactor belongs to the Federal State-Owned Unitary Enterprise MINING & CHEMICAL COMBINE (MCC) 53, Lenin Str., Zheleznogorsk, Krasnoyarsk Territory, RUSSIA, 660972.

The Krasnoyarsk neutrino laboratory is built in the MCC underground territory.

There are two places to install the detectors. One of them at ∼115 m from the reactor is 10 m high 15×15 m square room. The other is a 125 m long, 11.5 high and 15 m wide corridor at ∼1000 m from the reactor. More information on neutrino at Krasnoyarsk can soon be found at *http://www.lngs.infn.it/site/exppro/panagic/section_indexes/frame_particles.html* (click “Laboratories and experiments”, then “Underground and underwater laboratories” and go to “Krasnoyarsk neutrino laboratory”).

Zheleznogorsk is located at about 70km from Krasnoyarsk on the bank of the Yenisei River. Zheleznogorsk is a very nice and clean town built in direct neighborhood to the Siberian taiga, rich of birds and animals. There is a beautiful large lake in the center of the town. Picturesque hills surround the town center. A musicale theatre, hotel, rest home, restaurants, a lot of shops are in Zheleznogorsk.. The weather is comfortable; the number of sunny days is the same as in resort Sochi (at the Black Sea). Winter is cold but not so much compared with Moscow, air is dry. The summer and autumn are warmer and sunnier than in Moscow.

Some information about tourism in Krasnoyarsk Territories is available at the site: *http://tlcom.krs.ru/kalinka/indexe.htm*,
tours *http://tlcom.krs.ru/kalinka/indexe.htm*

Every day there are flights from Moscow to Krasnoyarsk airport. Big comfortable airbus IL86 in 4.5 hours time brings you from Moscow to Krasnoyarsk with good service of KrasAir company and a special minivan in 2 hours carries you from Krasnoyarsk airport Yemelianovo directly to the center of Zheleznogorsk.

MINING & CHEMICAL COMBINE has two own rest homes; one of them is in the town territory near the forest and another outside of the town not far from it on the bank of Yenisei River. Both of them have conference halls, comfortable living rooms and dining rooms.

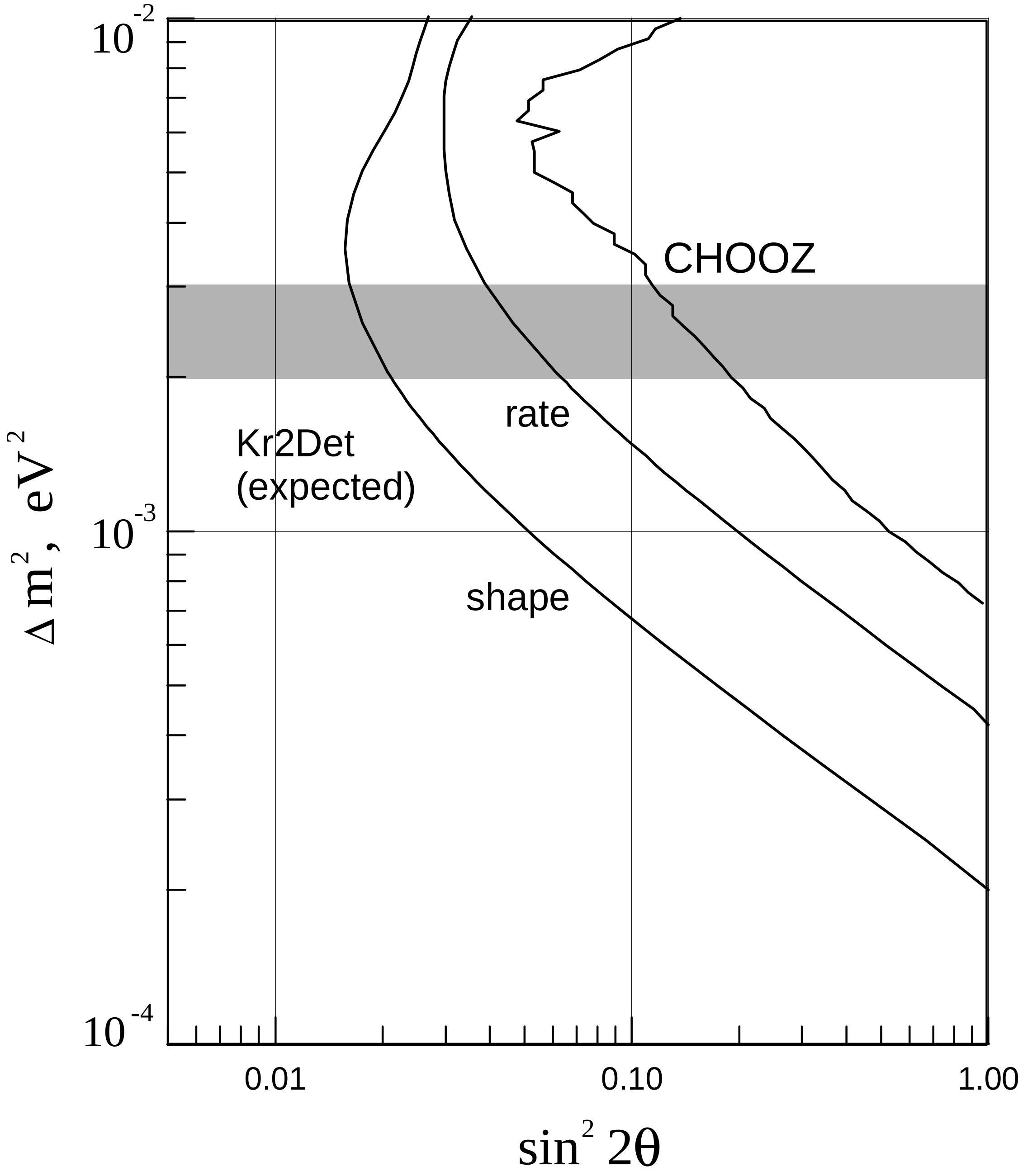


Figure 1. Reactor antineutrino oscillation plots. Curves “CHOOZ”, “Kr2Det” (expected) “shape” and “rate” are 90% CL $\bar{\nu}_e$ disappearance limits. The Kr2Det limits are obtained assuming 40 000 detected antineutrinos in the far detector, 10:1 effect to background ratio and systematic uncertainties σ_{shape} = 0.5% and σ_{rate} = 0.8%
The shaded area represents the most probable atmospheric neutrino mass parameters region.

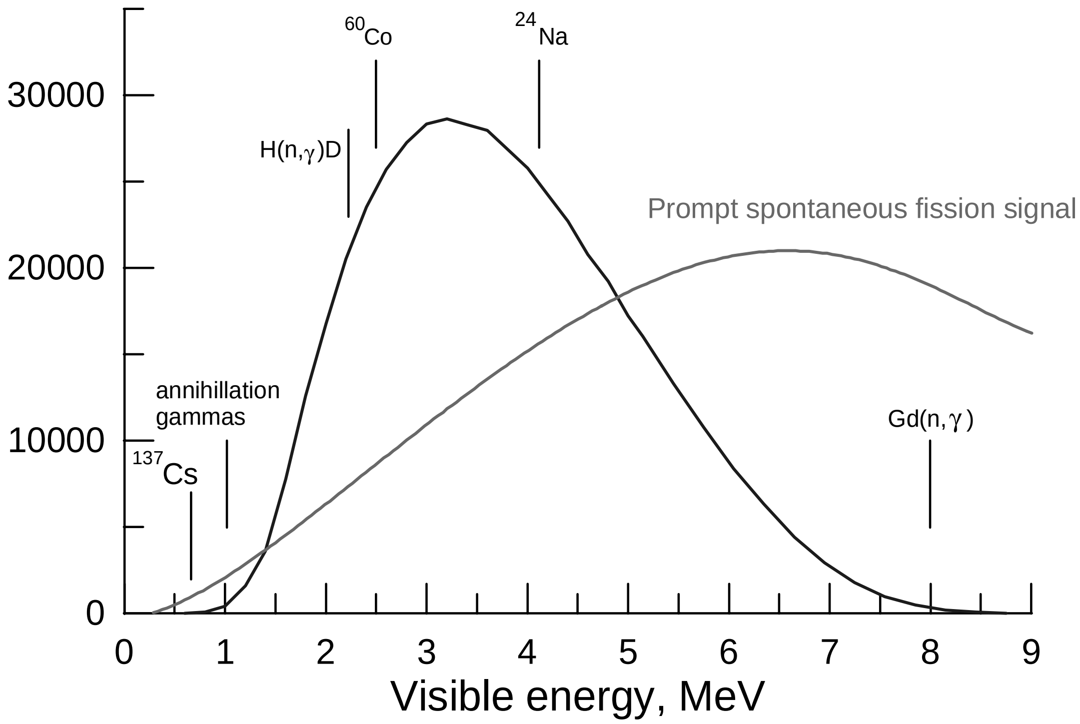
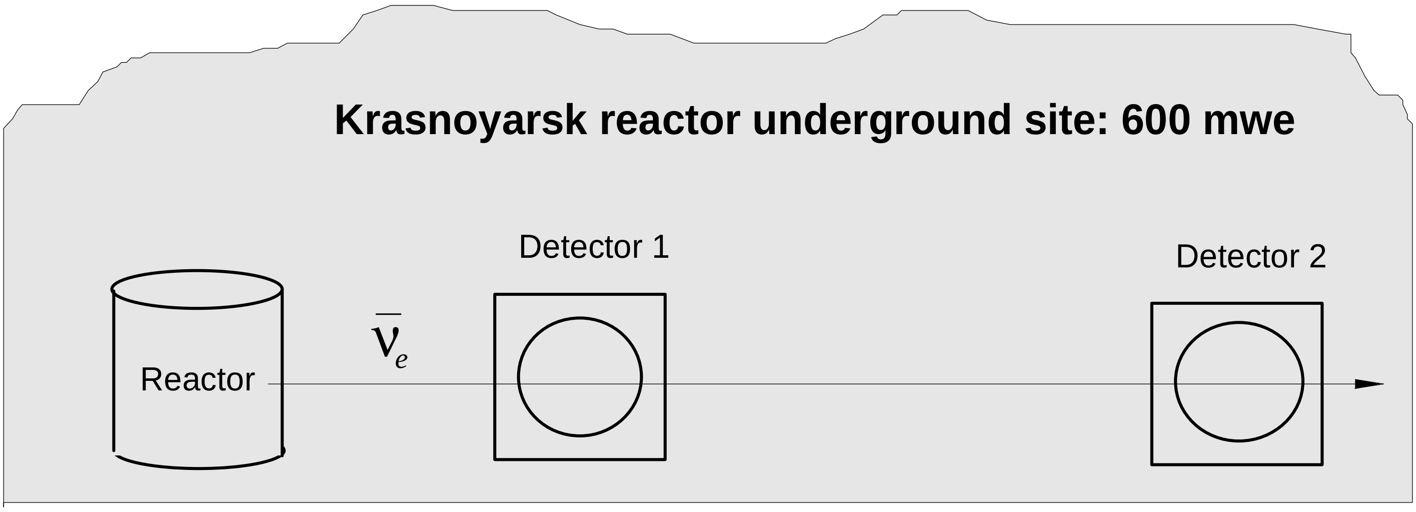


Figure 2. Positron visible energy spectrum.



	115 m	1000 m
Target:	**46 t**	**46 t**
Rate:	**4200/day**	**55 /day**
S:B	**>>1**	**~ 10:1**

Figure 3. Scheme of the Kr2Det experiment.

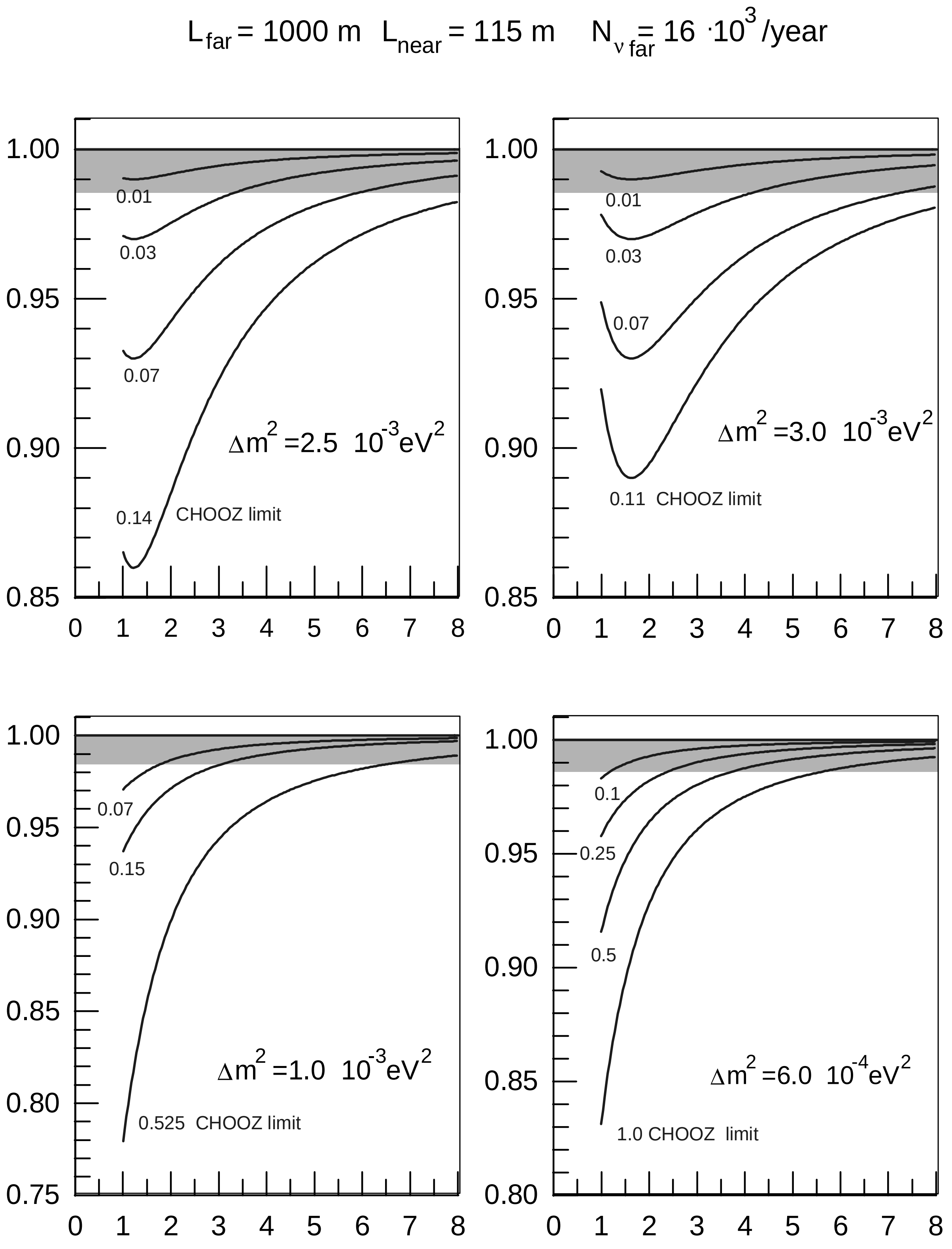


Figure 4. Calculated ratio of positron spectra $S(E_e)_{far} / S(E_e)_{near}$ for some oscillation parameters.
Values of $\sin^2 2\theta$ are shown at the curves

PMT type EMI 9350 Diameter - 8 inches
Coverage - 20%, PMT Number - 842

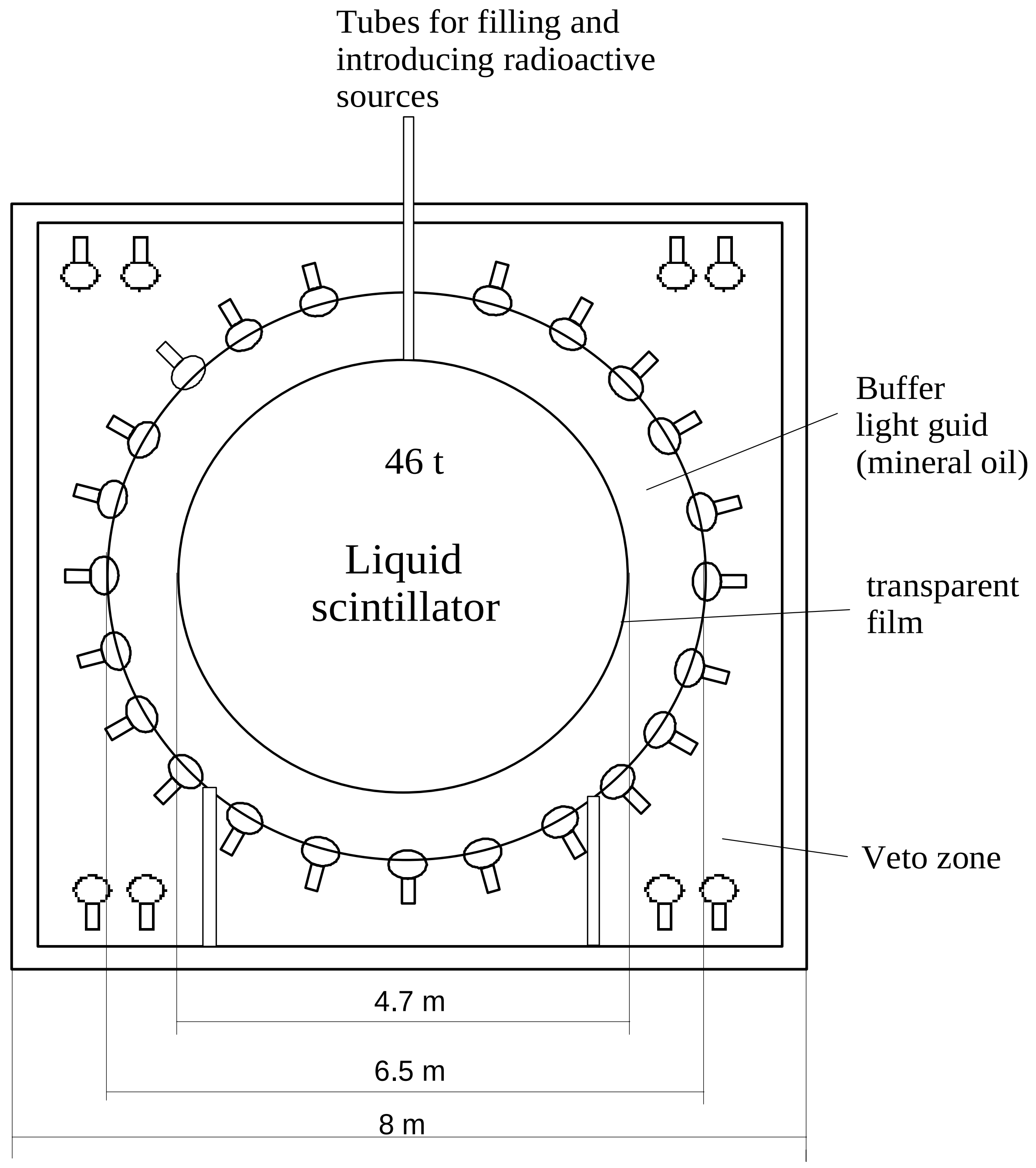


Figure 5. The Kr2Det $\bar{\nu}_e$ spectrometer (schematic)